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Combining environmental and economic factors to evaluate the reuse of electrical and electronic equipment – a Swiss case study

Roland Hischier^{*}, Heinz W. Böni

Empa, Technology & Society Laboratory, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland



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ABSTRACT

One key strategy which can be used to promote a Circular Economy is 'reuse'. This is particularly relevant for Electrical and Electronic Equipment due to its often rather short use phase as well as its resource-intensive production phase. The present study aimed to investigate the environmental and economic relevance of promoting the reuse of (waste) electrical and electronic equipment in Switzerland. To do so, a simplified life cycle assessment approach was combined with a calculation of the total cost of ownership of a device. These calculations were made for five different types of device: washing machines, refrigerators, televisions, laptop computers, and smartphones. Results showed that from an environmental perspective, smartphones or laptop computers, whose dominant environmental impact comes in their production phase, should be reused independently of their age, whereas for the three other devices, age is a decisive factor. Adding on the economic factor—that reuse should result in lower costs—led to the conclusion that all older devices except for refrigerators would have to be 'sold on' at no cost in order for their reuse to make sense economically. In addition, there should be a consideration of whether buying second-hand equipment replaces a new device or results in an increase in the total stock of devices, as old and new ones are run in parallel, creating a typical rebound situation. Public authorities should thus be more active in sharing information and raising awareness about the possibilities for repair and reuse.

1. Introduction

The term *circular economy* (CE) has become a buzz word over the past few years. The Ellen MacArthur Foundation's activities and publications played an important part in this (e.g., [Ellen MacArthur Foundation 2012, 2013](#)). Its initiatives received much public attention, particularly due to its success in getting global business leaders involved at an early stage and putting pressure on the authorities. It recently also published a first report on reuse aimed at tackling the packaging sector ([Ellen MacArthur Foundation 2019](#)). A study by Vanner and colleagues aimed at 'identifying potential circular economy actions, priority sectors, material flows and value chains' across Europe concluded that the electronic and electrical equipment (EEE) sector was among the priority sectors to deal with: accelerating the CE for EEE would result in significant societal benefits, and European Union policy would have to play a crucial role ([Vanner et al., 2014](#)). The Ellen MacArthur Foundation paper entitled '*Circular consumer electronics: an initial exploration*' examined how a CE approach might look for the consumer electronics industry and concluded that such a transition would have potential

benefits for the environment, society, and the electronics industry. However, it also concluded that many questions remained unanswered ([Ellen MacArthur Foundation, 2018](#)). The European Commission's March 2020 '*New Circular Economy Action Plan*' announced that concrete actions would be launched in the electronics and information and communication technologies (ICT) sectors, among others, due to the fact that they not only used lots of resources but had a high potential for circularity ([European Commission 2020](#)).

A search in SCOPUS using the keywords "(circular economy) AND (waste electronics and electrical equipment OR electronics and electrical equipment OR household appliances OR electric device)" resulted in 64 hits, with 54 from the period 2016–2019. This emphasized the issue's growing relevance among scientists all over the world. Although, as yet, no comprehensive and commonly accepted definition of 'circular economy' exists ([Desing et al., 2020](#); for a review of various approaches, see [Kirchherr et al., 2017](#)), there is agreement on the fact that the current (linear) business production model is extremely resource-intensive. That model is therefore far from the requirements stated within United Nations Sustainable Development Goal number 12, 'Responsible

^{*} Corresponding author.

E-mail address: roland.hischier@empa.ch (R. Hischier).

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consumption and production' (UN 2012). China is among the countries most actively implementing the principle of circularity into its economy. 'Reuse' is a relevant and key element in its approach (Cooper and Gutowski 2017) because the first use phase is often relatively short in the resource-intensive EEE sector. In Europe, the 'Waste Electrical and Electronic Equipment (WEEE) Directive' (European Union, 2012) aims to facilitate the separate collection and processing of WEEE to enable greater possibilities for reuse and material recovery at a device's end-of-life. Only 2% of the WEEE collected in Europe today gets prepared for reuse, although almost 70% is recycled (statistical data for 2015, retrieved from <https://ec.europa.eu/eurostat/web/waste/key-waste-streams/weee>). Following their 2013 survey and interviews of representatives from around the world, Kissling and colleagues concluded that there were two interlinked difficulties: (i) access to a sufficiently large amount of good-quality used equipment, and (ii) accompanying legislation supporting, incentivizing, or enforcing that access (Kissling et al., 2013). The survey noted that securing constant access to quality products and processes would be among the most important factors required for success. Some years later, a Danish study by Zacho and colleagues concluded that there were potential environmental, social, and economic benefits to designing products for reuse; however, few such preparations were to be observed in the EEE sector (Zachó et al., 2018). Those authors described constraints on several levels (i.e., technological, organizational, and institutional) and conflicts of interests among the variety of actors involved, all of which hindered more widespread reuse of WEEE. In a similar context, Parajuly and Wenzel proposed a so-called "product family approach" as the conceptual framework for implementing a circular economy for the management of WEEE (Parajuly and Wenzel, 2017b). They argued that improving WEEE collection, adding a testing platform to a pre-sorting step, and processing all the devices in a family-centric system would enable the EEE sector to achieve circularity; however, they failed to produce comprehensive evidence for the applicability of their framework within Europe's current WEEE systems. Their study was limited by an incomplete selection of devices and its focus on economic aspects alone (Parajuly and Wenzel, 2017a).

Other authors have investigated the reuse potential of specific components and types of devices, e.g. looking at the potential for cascade utilization of the same device (Coughlan et al., 2018) or focusing on smartphones as the prime example of unsustainable, linearly-used EEE (Gurita et al., 2018; Makov et al., 2018). All these cases showed that—subject to a range of assumptions—steps could be taken towards more sustainability in the electronics sector. Canetta and colleagues recently reported on a methodology that could be used to assess improvements in the overall sustainability of CE practices in the consumer electronics sector. This included the identification of the most promising solutions and contexts for their application, together with some factors critical to success (Canetta et al., 2018). The applied methodology is a mixture of simplified or screening life cycle assessment (LCA) and scenarios about product life extensions, e.g., for mobile phones. It concluded that the reuse of mobile phones would indeed have potential benefits for the environment and the economy (Canetta et al., 2018). The study was limited to the environmental impact category of CO₂-equivalents, however. De Oliveira Neto and colleagues published a more comprehensive economic and ecological assessment of recycling and reuse covering the WEEE sector as a whole (de Oliveira Neto et al., 2017). However, their study—taking a small example of Brazilian and Swiss WEEE recycling companies as practical cases—did not use a comprehensive LCA approach in its ecological assessment but instead applied their own "Mass Intensity Factor", which represents one potential operationalization of the Wuppertal Institute's concept of material intensity per service unit. The latter is, however, a solely input-based assessment method.

The aim of the present research was to comprehensively analyze the potential environmental and economic significance of fostering further use or reuse of EEE, i.e., whether it makes sense for public

authorities to pass legally binding regulations, using Switzerland as a case study. According to Cooper and Gutowski (2017), reusing household appliances does not automatically result in overall environmental benefits. The main reason for this conclusion was the fact that not all reused appliances displace actual sales of new devices, although this would seem to be an indispensable condition. An additional reason was the fact that not all types of reused appliances have a lower life cycle impact than new devices. Their research suggested that a real increase in the reuse of products—replacing the purchase of new products and thus leading to a real reduction of environmental impacts—would be unlikely without regulatory pressure. The present study's initial focus was, therefore, on the question of whether there was indeed the environmental and economic potential for the further use or reuse of a subset of all devices that are currently going into Switzerland's WEEE recycling systems (previously described and assessed in, e.g. Hischier et al., 2005; Wäger et al., 2011). Its secondary focus was on whether that potential should be (further) promoted by government interventions. The objective of the study's environmental component was to identify for which EEE (type, age) further use or reuse actually makes sense. Especially with older devices, a situation may arise where the environmental impact of additional use is greater than that of buying a new device. However, the potential economic savings of purchasing a second-hand device rather than a new one may be a critical deciding factor, and the potential environmental benefits of a new device may be of secondary concern to the consumer. The present manuscript reports on our investigation's methodology and results with regards to the economic and environmental benefits of reuse, taking Switzerland as a case study. Section 2 briefly explains the methodology applied to combine the ecological and economic analyses, and it summarizes the representative models used for different types of electric and electronic devices. Section 3 gives an overview of that methodology's results, and Section 4 concludes by highlighting the main lessons learned coming out of these results for the various types of electric and electronic devices examined.

2. Materials and methods

2.1. Examined devices

Our research could not cover every type of device; therefore, we investigated a representative selection of the wide range of household goods from the EEE sector (Hischier et al., 2020). These devices were washing machines, refrigerators, televisions, laptop computers, and smartphones. Data were mainly based on the topten.ch internet platform's information about the best devices sold in 2016, with additional data from other sources. The key figures listed in Table 1 were used to model the environmental and economic impacts of the examined devices.

The technical characteristics (e.g., energy consumption) of devices change over time, therefore, a new device bought in 2025 will consume a different amount of energy than a device purchased several years earlier, yet deliver the same service. Supplementary Table S.1 summarizes the assumed future development of the key (technical and economic) characteristics of the five examined devices.

2.2. Scope of study

Because the initial manufacturing efforts for a reused device have to be allocated differently, we must distinguish two different reuse situations: (i) extended device use by the same owner or user (e.g., after repair), and (ii) purchase of a second-hand device by a different user. In situation one, there is no change of user, i.e., the total impact of production is accounted for by this user. In situation two, the entire production of the device is also allocated to the first user (as they voluntarily decided not to continue using a device, which might have

Table 1

Key figures for the devices examined (reference year 2016).

	Washing Machine	Refrigerator	Television	Laptop Computer	Smartphone
Type	8 kg capacity	191 L (cooling) 66 L (freezing)	51" screen (diagonal)	15.6" screen 80% HDD/20% SSD	Android- or iOS- based device
Price	CHF 1700	CHF 1750	CHF 900	CHF 1000	CHF 700
Weight	77.8 kg	68.4 kg	15.1 kg	1.93 kg	0.136 kg
Lifetime	15 years	15 years	10 years	8 years	5 years
Electricity	113 kWh/year	149 kWh/year	88 kWh/year	24.8 kWh/year	4 kWh/year
Water	9500 L/year	—	—	—	—
Source(s)	Average of 10 best devices according to www.topten.ch	Average of 10 best devices according to www.topten.ch	Average of 10 best devices according to www.topten.ch	Tecchio et al., 2018 , VITO and Viegand Maagøe, 2017	Hischier et al., 2013

become WEEE). Therefore, the scope, time period covered, and the life cycle stages included in the two situations are different. In situation one, the relevant time horizon starts in the past (including the production impact of the device whose use may continue), whereas in situation two the time horizon starts at the time of second-hand purchase, i.e., from the moment of the decision to buy and reuse a second-hand device, ignoring its past use (and thus its production phase). Fig. 1 contrasts these two situations using the example of a washing machine, where the first device is purchased in 2010 and the question of its further use is asked in 2016. Hence, the study's time horizon is from 2010 to 2025 (end of life for the first device) in situation one (i.e., the further use question), whereas for situation two (i.e., the washing machine's reuse as a second-hand device) the time horizon is from 2016 to 2031 (i.e., until the end of the new device's technical lifetime). In both cases, the duration is equal to the device's technical lifetime—i.e., 15 years in the case of a washing machine.

Because of our focus on the government's perspective, i.e., whether the reuse of devices sent for recycling should be promoted and regulated, the present research only considers situation two (right-hand part of Fig. 1), i.e., the eventual reuse of such devices (and thus it covers the period from 2016 to 2031). The continued use of devices (that the user owns already) is not considered.

2.3. Environmental analysis

This part of the analysis used a simplified life cycle assessment (LCA) approach. LCA is the most comprehensive, well-established, and well-developed framework for quantifying a product's or a system's environmental and human health impacts over its complete life cycle: LCA thus allows comprehensive environmental sustainability assessments (Ness et al., 2007). As described by Rebitzer et al. (2004), the roots of this framework can be found in 1960s energy-related research and formal pollution prevention research initiated in the 1970s. Today, LCA is applied to a wide variety of products and to any decisions where environmental impacts are of interest. The present study is considered a simplified LCA as all the calculations were made using Microsoft Excel, using the life cycle impact assessment (LCIA) results of the individual datasets from version 3.3 (the recycled-content system model) of the ecoinvent database (ecoinvent Centre, 2016). Within this Excel spreadsheet, the LCIA results from the ecoinvent datasets applied (i.e., the present study's background data) were combined and linked with the related key characteristics of the different devices (i.e., the foreground system).

This foreground system covers the entire life cycle of each of the five examined devices, split into production (including manufacturing materials), use, and end-of-life treatment (i.e., all recycling and disposal

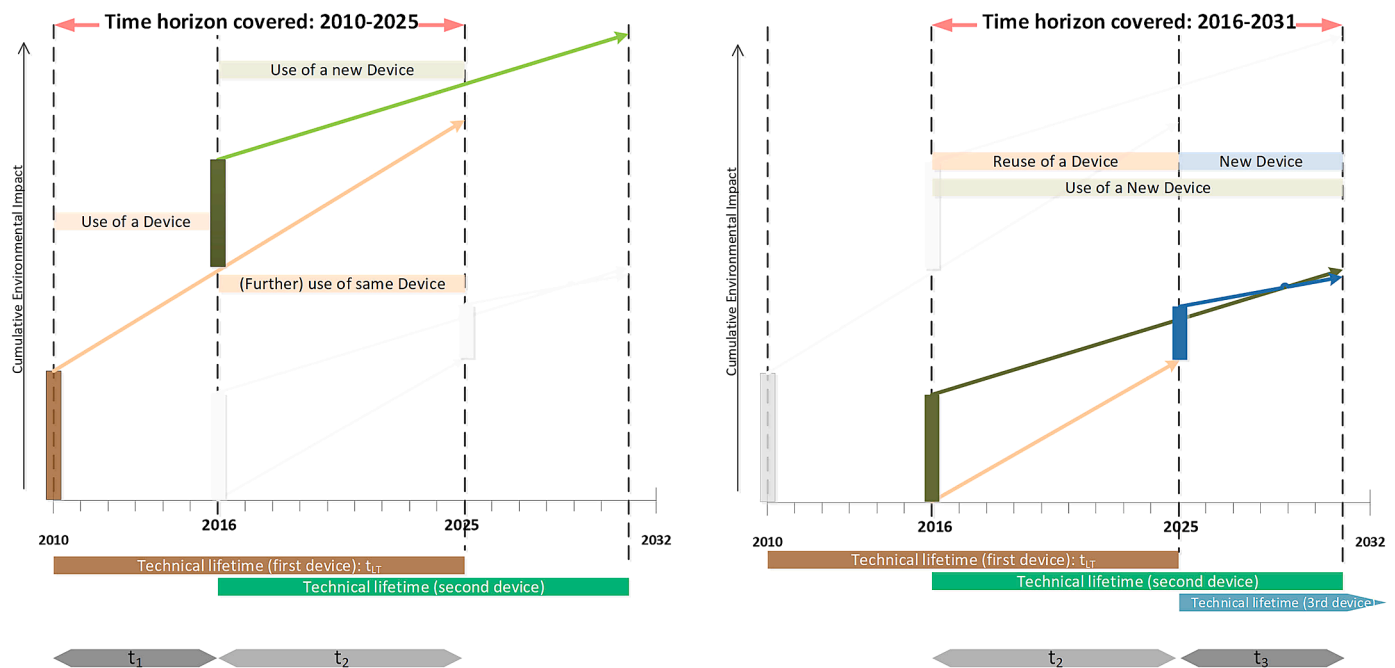


Fig. 1. Scope of the study for the two different situations, i.e. the continued use of the first device (left-hand figure) and reuse of a (second-hand) device (right-hand figure). The thick vertical bars represent the immediate impacts of washing machine production, whereas the diagonal lines represent the impacts of washing machine use over time.

efforts, and the resulting benefits due to the availability of secondary materials). For the production phase, composition and production-effort information for a typical device (deduced from the literature) was combined with its respective data from the ecoinvent database. The applied datasets and input values are summarized in Supplementary Table S.2. All calculations for the use phase assumed use in Switzerland of a device produced in 2016; they applied Table 1's consumption data in combination with the ecoinvent datasets for Switzerland's low-voltage electricity and tap water markets. Consumption values for older or newer devices were adjusted in accordance with the information presented in Supplementary Table S.1 to calculate the respective impacts of their use phases. The distribution phase (i.e., transport from the production site to the user) was excluded due to its low ecological relevance in these devices' overall life cycles. For the last life cycle phase of end-of-life treatment, disassembly efforts and further treatments (i.e., disposal or recycling) of various device fractions were modelled (representing a state-of-the-art WEEE recycling process), and the resulting secondary recycled materials and energy used were compared to the avoided burdens of producing the same amount of primary new materials. Supplementary Table S.3 summarizes the datasets used for these recycling efforts and the avoided burdens. All these calculations were analyzed using the following environmental impact categories: global warming potential (GWP) in kg CO₂-equivalents (CO₂-Eq) (Bourgault, 2015); total consumption of fossil energy carriers in the form of (non-renewable) cumulative energy demand (CED), expressed in MJ-Eq; and the overall environmental impact of the examined system using the ecological scarcity method (Frischknecht and Büsser Knöpfel, 2013), expressed in Swiss Eco-points or UBP (German for "Umweltbelastungspunkte"). As stipulated in a recent publication by one of the present authors, "these three impact categories are often used in Switzerland as overall indicators of potential impacts in simplified LCA studies. They represent many of the most relevant environmental issues in society today (GWP, CED) and, through the third factor in particular, a 'true and fair view' of the overall potential environmental impacts (at least from the point of view of the Swiss Government, who commissioned the method of ecological scarcity)" (Hischier, 2018). In agreement with the commissioner of the present study, these factors were also considered adequate for our analysis of the environmental potential for the reuse of electric and electronic devices in Switzerland.

2.4. Economic analysis

On the cost side, a simple calculation of the total costs of using any of the devices represented the total cost of ownership (TCO). According to Ellram, "TCO is a purchasing tool and philosophy which is aimed at understanding the true cost of buying a particular good or service from a particular supplier" (Ellram, 1995). TCO is close to the concept of life cycle costing (LCC), described by Sherif and Kolarik as "an analysis technique which encompasses all costs associated with a product from its inception to its disposal" (Sherif and Kolarik, 1981). However, whereas LCC also comprises the costs related to a good's conception and design (due to its product perspective), TOC adopts the user (or owner) of the good's perspective (Saccani et al., 2017), so the latter approach was the more adequate for the present study. We calculated TOC simply by summing the device's purchase price (new or second-hand) and the costs of electricity and water (for the washing machine) consumption during the use phase. In Switzerland, the end-of-life phase and WEEE treatment are not subject to any additional costs thanks to an advanced recycling fee (ARF) that is an integral part of the purchase price of electric and electronic equipment (Widmer et al., 2005). It was assumed that the purchase prices of second-hand devices equaled 50% of their remaining value, assuming a linear depreciation of the initial purchase price over the device's entire technical lifetime (both values are reported in Table 1, above). We applied fixed prices of 0.20 Swiss Francs per kWh of electricity and of 4 Swiss Francs per m³ of water during active use.

3. Results

3.1. Environmental analysis

A first step calculated the overall life cycle for each of the five devices (based on the key characteristics summarized in Table 1). Fig. 2 shows the resulting use phase contributions (expressed in Swiss Eco-points) to the overall life cycle, assuming use in Switzerland over the devices' technical lifetimes listed in Table 1.

About 2% of a smartphone's overall environmental impact is related to the use phase, whereas well over 50% of a washing machine's or a refrigerator's environmental impact comes from the electricity consumed in the use phase. No further environmental analysis is therefore necessary for smartphones: it can simply be specified that the longer they are in use, the lower their (environmental) impacts are; i.e. reusing such devices is always the best solution from an environmental point of view. Indeed, these results confirmed a Swiss study (Dettli et al., 2014) which showed that some devices' overall environmental impacts were dominated by use (and questions about their continued use have to be evaluated carefully), whereas other devices' environmental impacts were clearly mostly in production (and thus continued use or reuse is worthwhile). Thus, further environmental analysis was only carried out for the four remaining device categories, i.e., washing machines, refrigerators, televisions, and laptop computers.

Fig. 3 then shows the environmental saving potential of reusing these four devices (in comparison to purchasing a new device, set at 100%) as a function of the actual age of this second-hand device (ranging out to one or two years before the device's expected overall technical lifetime, as indicated in Table 1).

As this figure shows, the newer a device is, the greater the potential environmental impact reduction of reusing it. Whereas the factors of GWP and UBP show quite comparable age and impact reduction pictures, the factor of CED shows a much lower impact reduction potential. Using a minimum target impact reduction potential of 10% (the bold, dashed red line in Fig. 3) as a key criterion—and CED as the indicator—refrigerators and washing machines over 3 years old should be replaced already. GWP and UBP, however, show impact reduction potentials above 10% up to an appliance age of over 10 years for both appliances. The greater production's contribution to a device's environmental impact (as shown in Fig. 2), the greater the resulting impact reduction potential. Reusing recent laptop computers, especially, could lead to potential environmental impact savings going beyond 50% (compared to purchasing a new device) for the factors of GWP and UBP. Indeed, these two factors show a reduction potential of above 10% up to a device age of 7 years, i.e., indicating (similarly to the smartphone) that longer use almost always makes sense (from an environmental impact perspective). In the cases involving white goods (i.e., washing machines and refrigerators), the variability in the assumed improvements in production processes (ranging from 0% to −2% per year, as reported in Supplementary Table S.1) shows-up in the results, e.g., reducing the impact reduction potential of 5-year-old devices by 2.5% to 3.5%.

3.2. Economic analysis

Our economic analysis applied two different boundary observations: (i) for a given age of a reused device, the calculation of the net TCO losses or savings in relation to the percentage of the price for the reused device compared to the price of a new device; and (ii) for a given minimal reduction in the TCO, the maximum price of a reused device as a function of the device's age. Fig. 4 shows the results of these two approaches for 5-year-old devices and for a 20% reduction in the TCO, respectively.

Fig. 4A shows that 5-year-old ICT devices, such as smartphones or laptop computers, have to be free in order for the resulting TCO to be lower than the TCO of new ICT devices. From an economic point of view, such devices—even when they are acquired for free—never result in

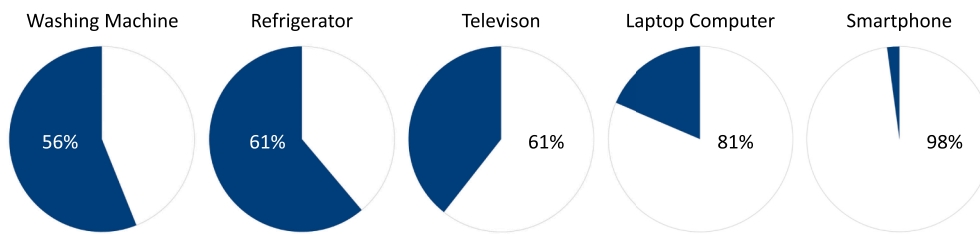


Fig. 2. Contributions of the use phase in Switzerland (dark segment) to overall environmental impact (expressed in Swiss Eco-points). The percentage value shows the dominant impact (i.e., the use phase for washing machines and refrigerators; production plus end-of-life for the remaining devices).

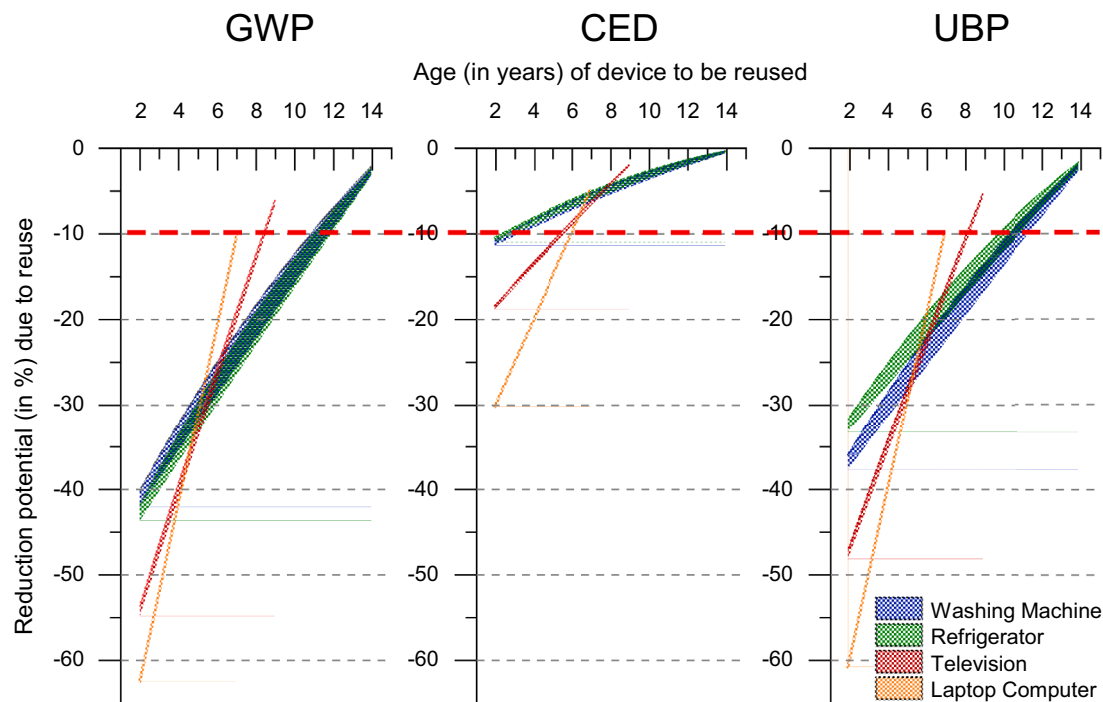


Fig. 3. Environmental saving potential of reusing a second-hand device (in comparison to purchasing a new device, set at 100%) as a function of this second-hand device's actual age. The dashed red line represents a reduction potential of 10% (set as this study's minimum target). The thicker ranges shown for washing machines, refrigerators, and televisions represent the variability in the reduction of production impacts according to the data in Supplementary Table S.1. The three impact assessment factors applied were GWP: global warming potential, CED: non-renewable, cumulative energy demand, and UBP: overall environmental impacts, expressed in Swiss Eco-points.

economic savings. The same diagram shows that the net TCO for the three other second-hand devices only becomes negative if they can be acquired at a very low price (e.g., less than 40% of the initial price in the case of the television). The same facts—shown in a different way—are visible in Fig. 4B. Even when they can be acquired for free, smartphones and laptop computers over 3 years old never result in a net TCO of -20% ; and the same is true for televisions more than 6 years old or washing machines more than 8 years old.

4. Discussion and conclusion

4.1. Combined environmental and economic analysis

The present research was born of two questions. Firstly, when is the reuse of second-hand EEE sensible from an environmental and economic point of view? And secondly, should the authorities take legal or other measures to promote the reuse of valid, working devices which would otherwise be sent for recycling? The results of our respective environmental and economic analyses of five different EEE devices (i.e., washing machines, refrigerators, televisions, laptop computers, and smartphones) were described in detail in the preceding section and are

summarized in Table 2.

Depending on the device and the environmental impact measurement category applied, the results of these environmental analyses show a rather diverse picture. In general, devices whose dominant environmental impact is in their production (such as smartphones or laptop computers) should be reused independently of their age. These results are in accord with the conclusions found in various references cited in this work's introduction (i.e., Canetta et al., 2018; Coughlan et al., 2018; Gurita et al., 2018), although these were mostly limited to analyses of devices' Global Warming Potential. For the other devices (i.e., washing machines, refrigerators, and televisions), age was decisive. Looking at overall environmental impact expressed in Swiss Eco-points (UBP), washing machines and refrigerators should not be used for more than about 10 years, whereas for a television the threshold is around 8 years. As mentioned at the beginning of this work, to the best of our knowledge, no comparable published study has yet assessed these types of devices in such a comprehensive way. A recent study by the same author, about the environmental impacts of household appliances in Europe (Hischier et al., 2020), also investigated a scenario involving similar changes in user behavior (i.e., increased reuse). This resulted in a comparatively low change in the overall impacts of the use of such

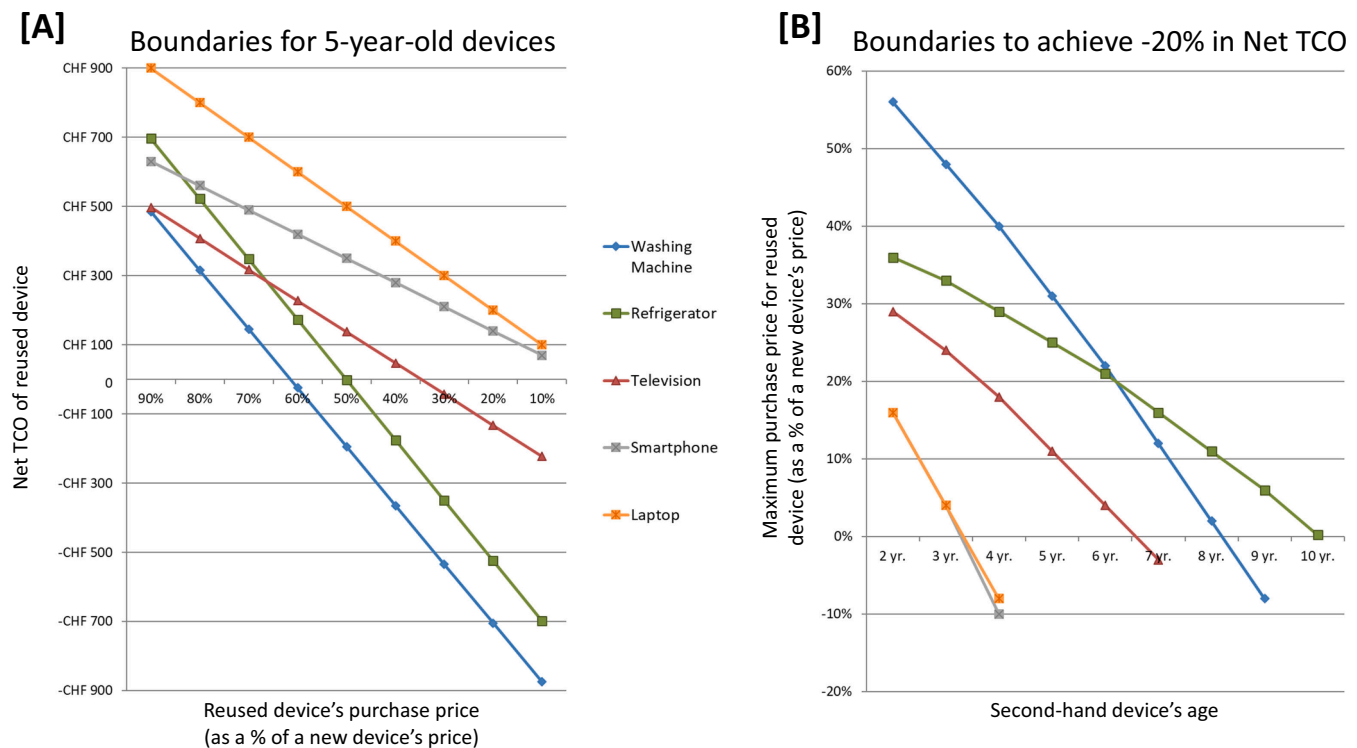


Fig. 4. Potential economic losses or savings shown as the Net TCO from reusing a 5-year-old device as a function of its second-hand purchase price (Fig. 4A), and as the maximum price for a second-hand device in comparison to the price of a new device, as a function of its age, necessary to achieve a 20% lower Net TCO (Fig. 4B). Examples from the figure: (Fig. 4A) A 5-year-old washing machine should not cost more than 60% of the price of a new machine in order for the TCO to be better than that of a new washing machine; (Fig. 4B) The maximum price of a 4-year-old television should not exceed 18% of the price of a new television provided that the TCO of the second-hand television is 20% lower than the TCO of the new television.

Table 2

Summary of the environmental and economic analysis results of five EEE devices.

	Washing Machines	Refrigerators	Televisions	Laptop Computers	Smartphones
(i) Environmental Analysis: maximum age of a second-hand device (in years) for its reuse to show a reduction in environmental impact of at least 10%					
CED / cumulative energy demand	2 years	2 years	5 years	6 years	***
GWP / global warming potential	10 years	10 years	8 years	***	***
UBP / overall environmental impact	10 years	9 years	8 years	***	***
(ii) Economic Analysis: maximum purchase price of a second-hand device (in% of the price of the new device) for the total cost of ownership (TCO) to be at least 20% lower than when purchasing a new device					
... for a 2-year-old device	56%	36%	29%	27%	16%
... for a 3-year-old device	48%	33%	24%	20%	4%
... for a 4-year-old device	40%	29%	18%	13%	
... for a 5-year-old device	31%	25%	11%	5%	
... for a 6-year-old device	22%	21%	4%		

*** =environmentally always better to reuse this device.

devices by an average European citizen over one year, which is in line with the present results—bearing in mind the relatively long life-times of such devices and the fact that, especially in a European context, the use phase is the dominant life cycle phase.

If the economic aspect is also taken into account, the overall assessment results for the five devices are as follows:

- Washing machines: From an economic perspective, 8-year-old devices should be passed on free of charge, whereas from the environmental perspective, devices about 10 years old should be replaced in order for both dimensions to remain on the positive side.
- Refrigerators: The picture is similar for these white goods, i.e., from an environmental perspective, a 9- or 10-year-old device could still be reused and, from an economic perspective, the reduction in value is less than for the washing machine, resulting in a double "yes" for refrigerators up to about 10 years old.

- Televisions: From an environmental perspective, 8-year-old devices should still be used, however devices older than 6.5 years old would have to be passed on free of charge, in order for reuse to be economically viable too.
- Laptop Computers: Reuse should always be a priority since their environmental impact is primarily related to production. Economically, reuse is only worthwhile for newer devices (over about 5.5 years old, they must be passed on free of charge).
- Smartphones: Similar to laptop computers, reuse is *a priori* always worthwhile and, again, from an economic perspective, this is only worthwhile for newer devices (over 3.5 years old, they must be passed on free of charge).

It should be noted, however, that many assumptions (see Table 1 and Supplementary Table S.1) are necessary to be able to answer the question about when reuse makes sense from both the environmental and

economic perspectives. The assumed technical lifetimes of 15 years (washing machines, refrigerators), 10 years (televisions), 8 years (laptop computers), and 5 years (smartphones) are an additional source of uncertainty, regarding the expected efficiency increases of new equipment on the one hand, and regarding the development of product and material composition and average weight on the other hand. The technological leaps observed in recent years, especially in energy-intensive appliances (like washing machines), cannot be adequately mapped on current models, however. These many assumptions and uncertainties thus limit the validity of our results somewhat, and instead, they reveal tendencies (which will have to be verified individually) rather than giving a perfectly accurate picture.

In conclusion, based on the calculations presented here, the initial questions—when is the reuse of second-hand EEE sensible from both an environmental and an economic point of view, and should authorities take legal or other measures to promote that reuse—have to be answered slightly differently depending on the perspective taken. From the environmental policy perspective, the answer is primarily based on environmental considerations and, accordingly, a focus on devices is appropriate when reuse makes sense for environmental reasons. Generally, this rule would apply to devices whose environmental impacts are dominated by their production phase.

4.2. Recommendations for policy measures

The extent to which public authorities should take specific measures to support the reuse of EEE depends on whether such devices already have a functioning second-hand market and whether those currently entering the recycling system are still at all marketable. This is where the second perspective—the consumer perspective—becomes relevant. In the end, any purchasing decision will be based on a person's assessment. A consumer will base their decision on the very difficult to assess economic advantage of a second-hand device over a new device. Thus, the purchasing decision will be based on price attractiveness in terms of the device's age and condition (particularly in the field of information technology and consumer electronics, but also with household appliances and tools). For devices with a significant cost of use (e.g., washing machines), a purchasing decision will often also include questions about energy and water consumption (and their related costs). Furthermore, a consumer should consider that the device's warranty will probably have expired; buying equipment with a long life but a higher susceptibility to defects may, despite an attractive price, make them decide against a second-hand device. Last but not least, is second-hand equipment being bought in place of new equipment or will it simply result in more old equipment running in parallel to new devices (e.g., an old refrigerator running in a household cellar)? This will result in a typical rebound effect. Thus, considering the present study's results with the general principles of the waste hierarchy (i.e., prevention–reduction–recovery–disposal; see Wolf, 1988), we conclude that government authorities should become more active in the following two fields:

- Public information and awareness-raising activities. A selective extension of the present model to other types of equipment, combined with inferred generally valid results, could be quite useful in helping consumers to make decisions about purchasing second-hand equipment or continuing to use their current device. The advantages and benefits of reuse need to be differentiated: it does not always make sense to continue to use a device (or acquire it second-hand), and doing so does not always replace the production of a new device.
- Activities in the field of equipment repair. Promoting and supporting the publication of repair guides can help to avoid usable devices—which a consumer would like to reuse rather than recycle—ending up in the WEEE recycling system. Appropriate measures on the consumer side (having an interest in continuing to use a device or to

make it usable again) may make further market interventions (e.g., by the authorities) superfluous.

Declaration of Competing Interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2020.105307](https://doi.org/10.1016/j.resconrec.2020.105307).

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